Divergence of electron and lattice temperatures in nanometer scale contacts and structures.

Mark E. Welland
University of Cambridge

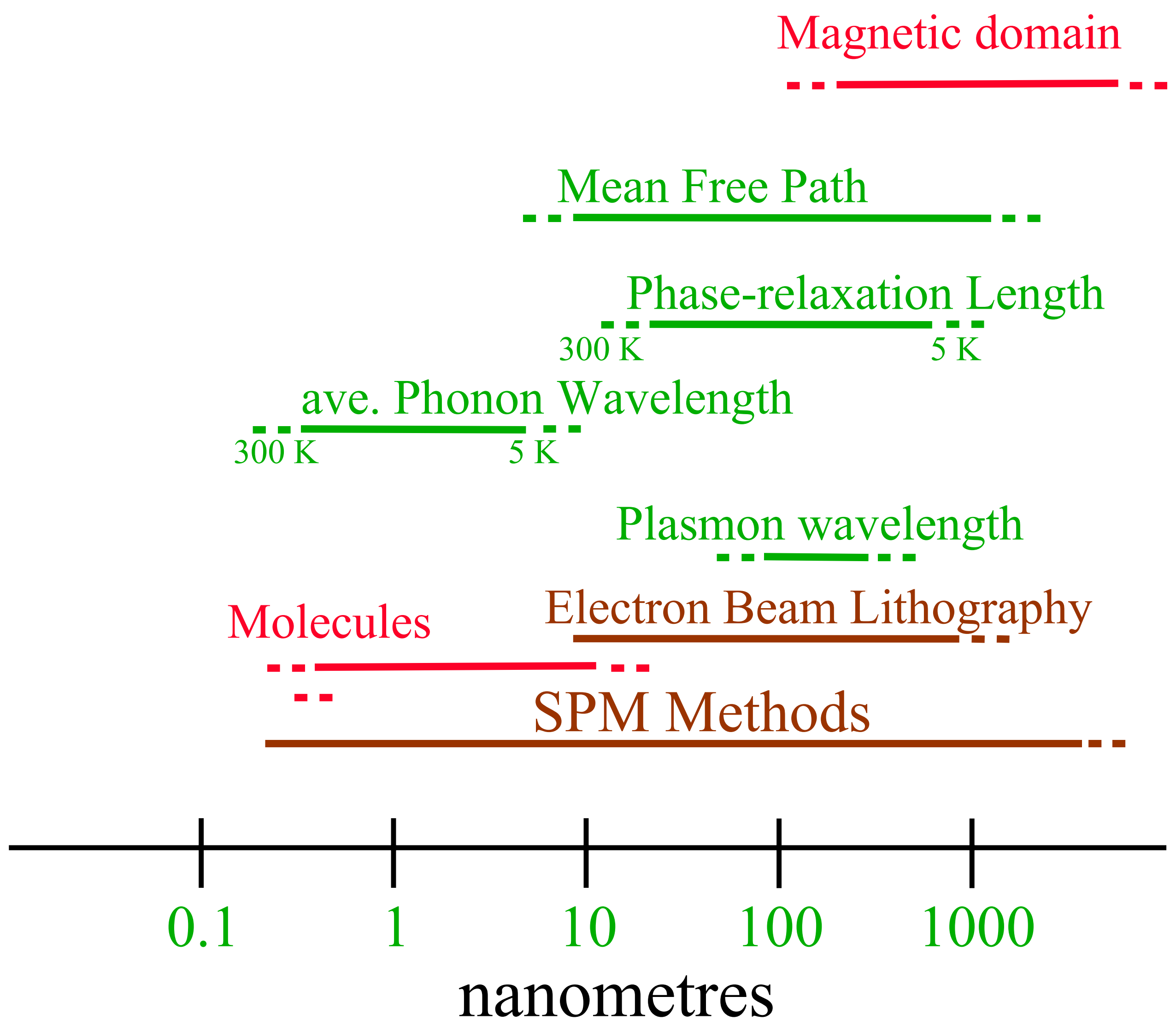
Email: mew10@eng.cam.ac.uk
Web: http://www2.eng.cam.ac.uk/~nano-www/

NANOSCALE
SCIENCE
LABORATORY

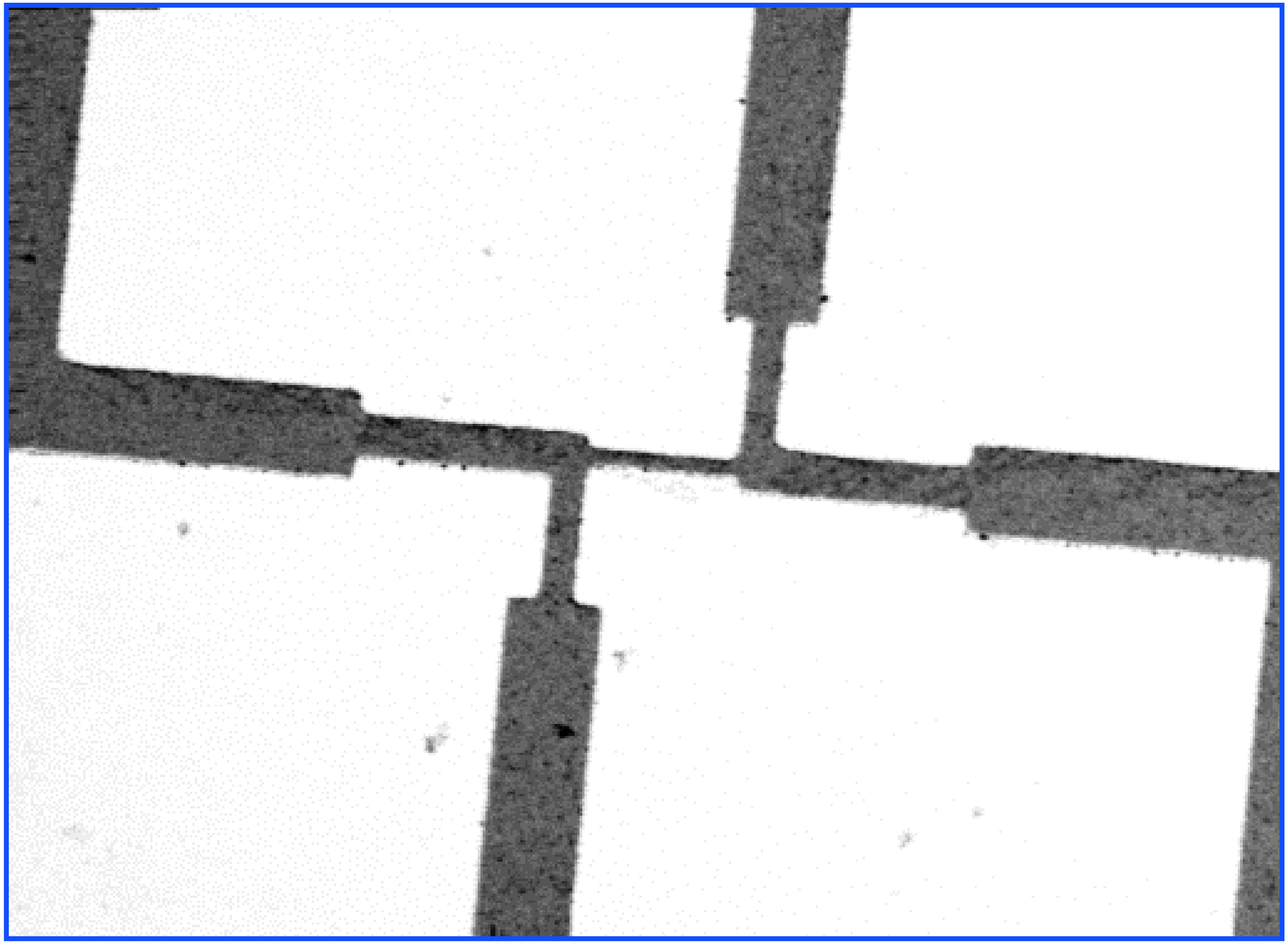
Overview

- **Length scales**
- **Thermal effects in metallic nanowires**
- **Heating in metallic point contacts**

Length scales

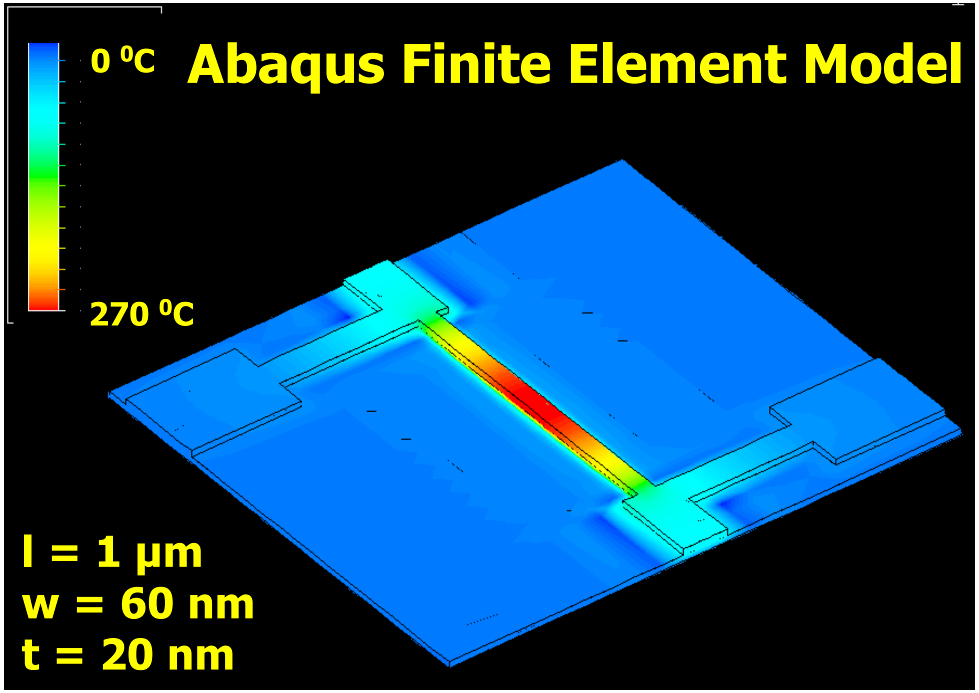


Metallic nanowires



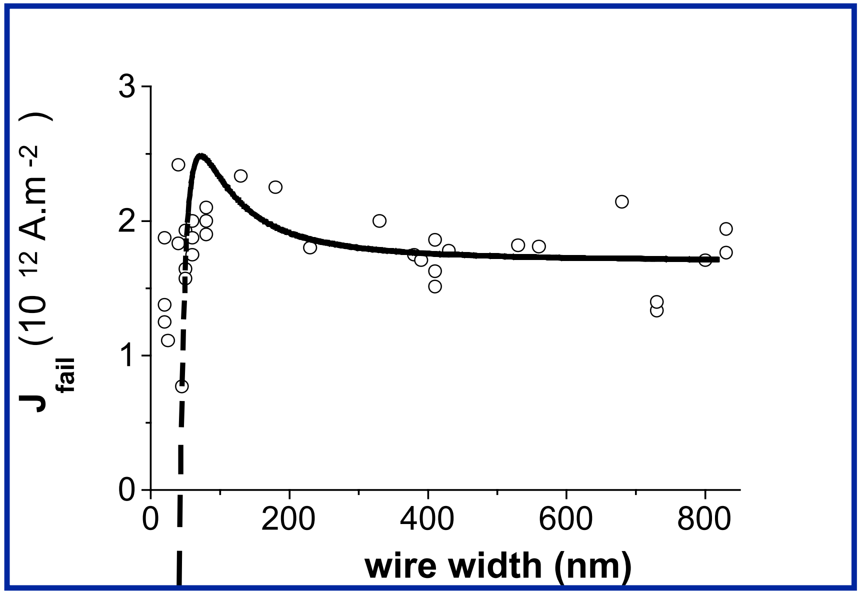
Failure mechanisms in Nanowires (width < 100 nm):

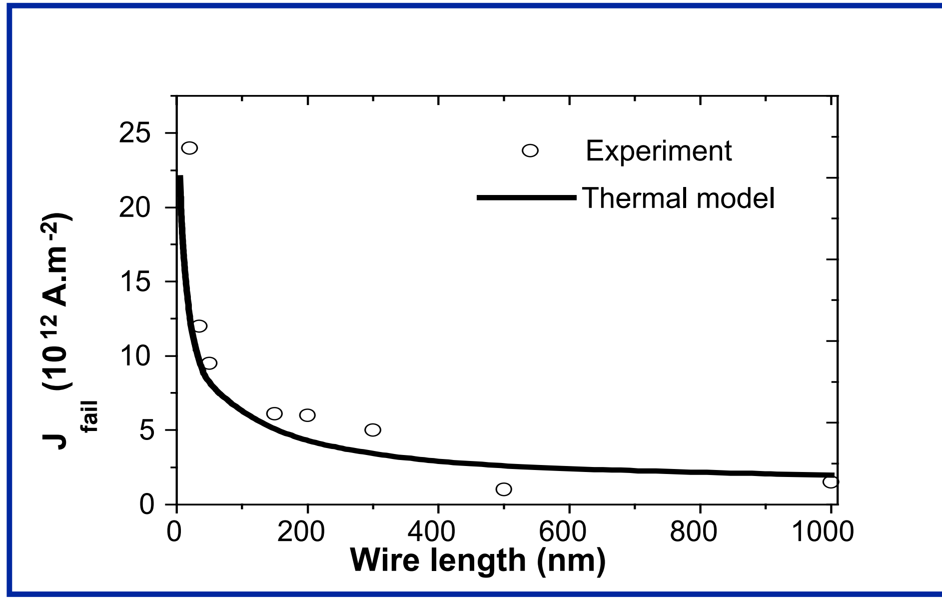
- current - induced thermal stress
- microstructure: polycrystalline/bamboo + thermal stress = restructuring
- local electric fields, high resistivity spots, can lead to locally enhanced electromigration



- The temperature of nanowires at high current densities (10^{12} A.m^{-2}) is expected to reach >200 ^{0}C

Dependence of dimensions on failure of current-stressed nanowires





- **1 μm long wires**
- **50 nm wide wires**

•Peak in J_{fail} for width ~ 100 nm may be due to suppressed electron-phonon scattering

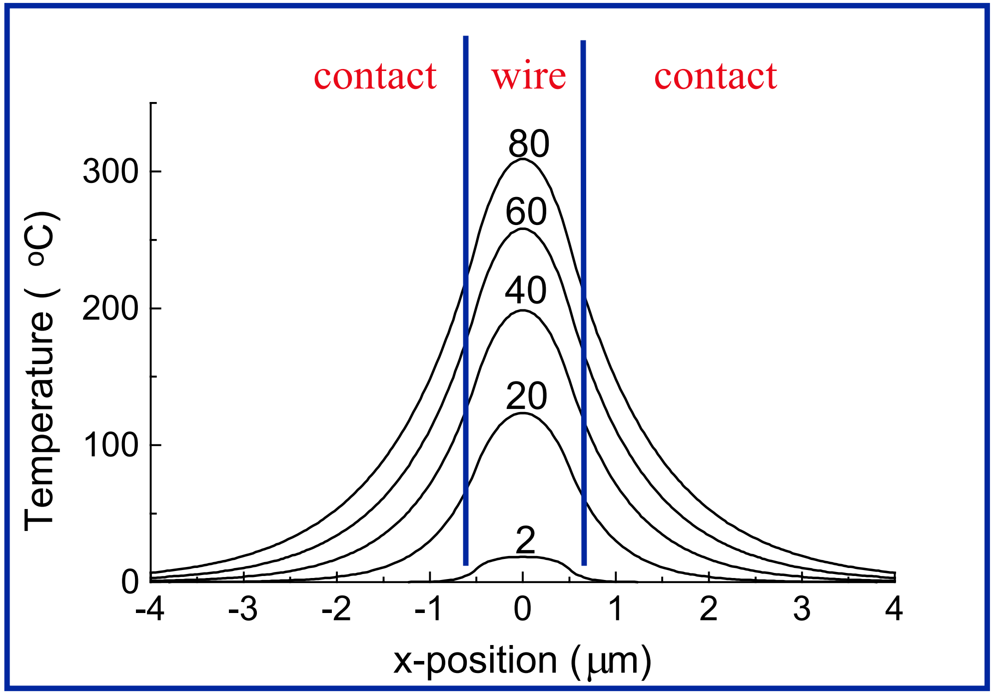
Heating of current-stressed nanowires

- **Thermal model: solve Poisson's equation analytically:**

$$\nabla^2 T - m^2 T + \frac{Q}{k} = 0$$

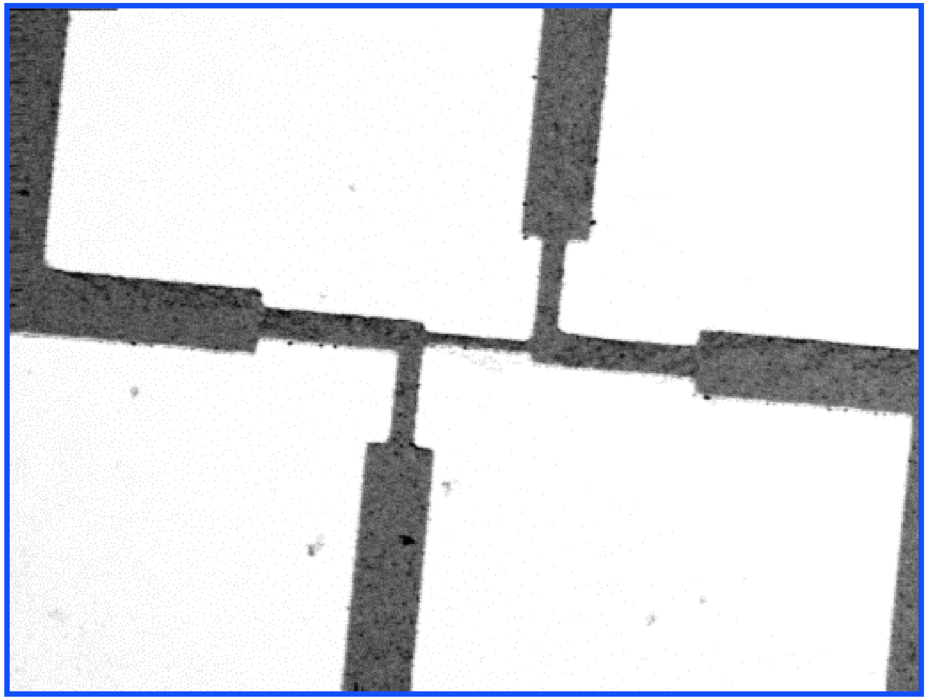
heat loss — heat generation

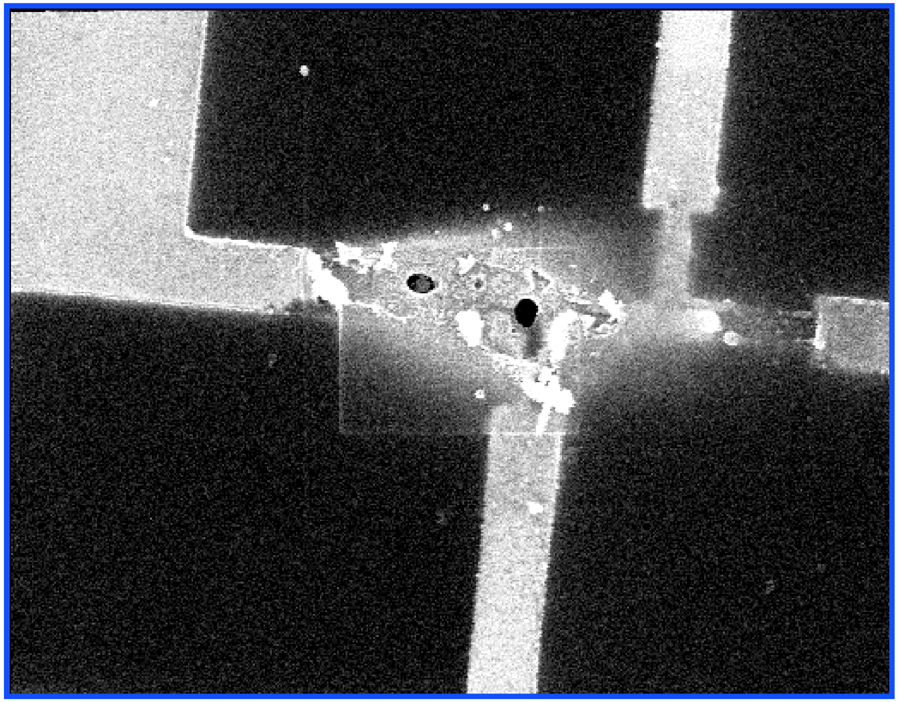
Temperature in 1 μm long wire for various substrate oxide thicknesses, $J=2*10^{12}$ A.m^{-2} :



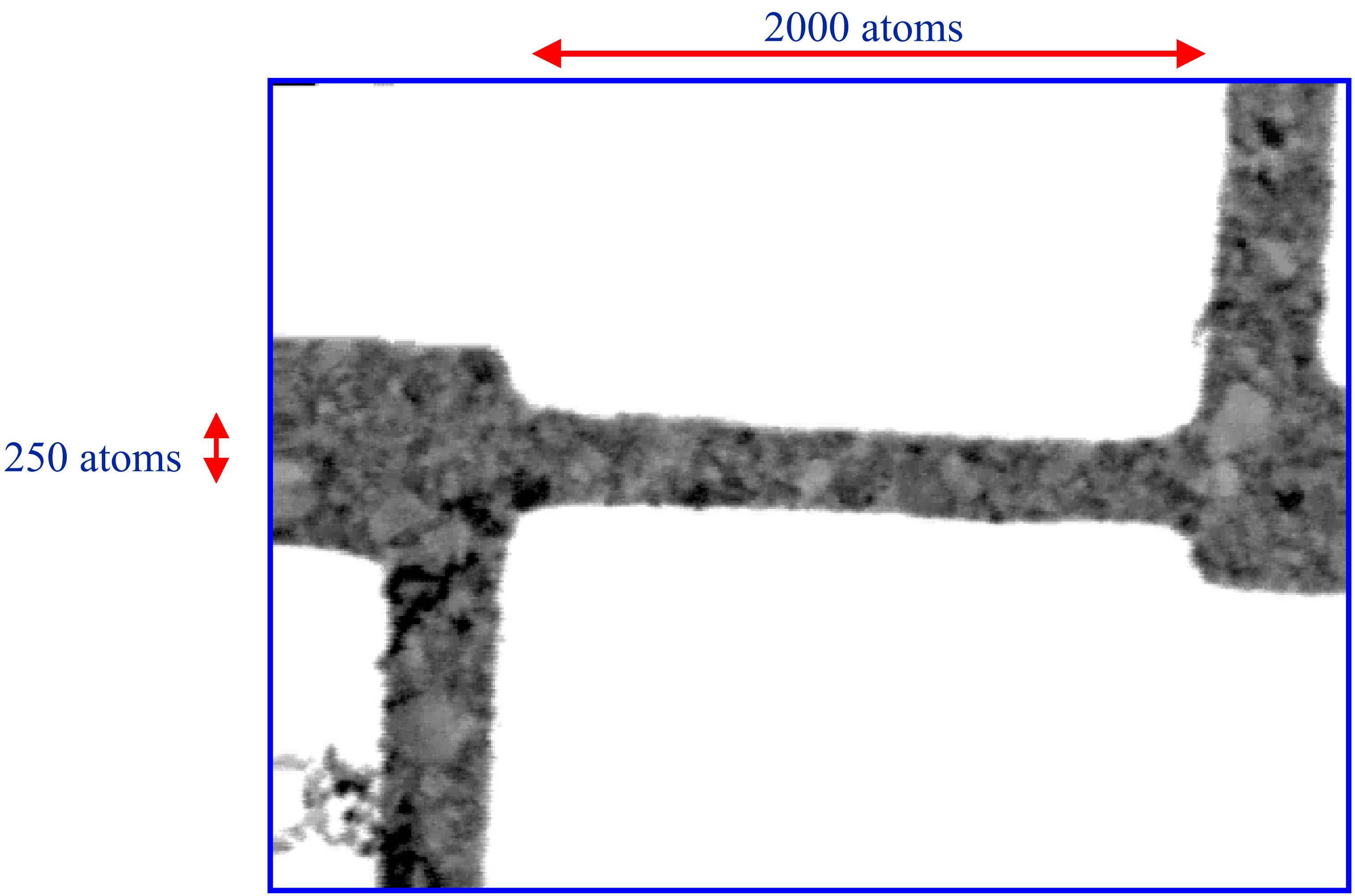
- **No explicit width dependence**
- **exponential length dependence**
- **1/(oxide thickness) dependence**
- **Temperature peaked at centre**

Metallic wires at the nanometre scale

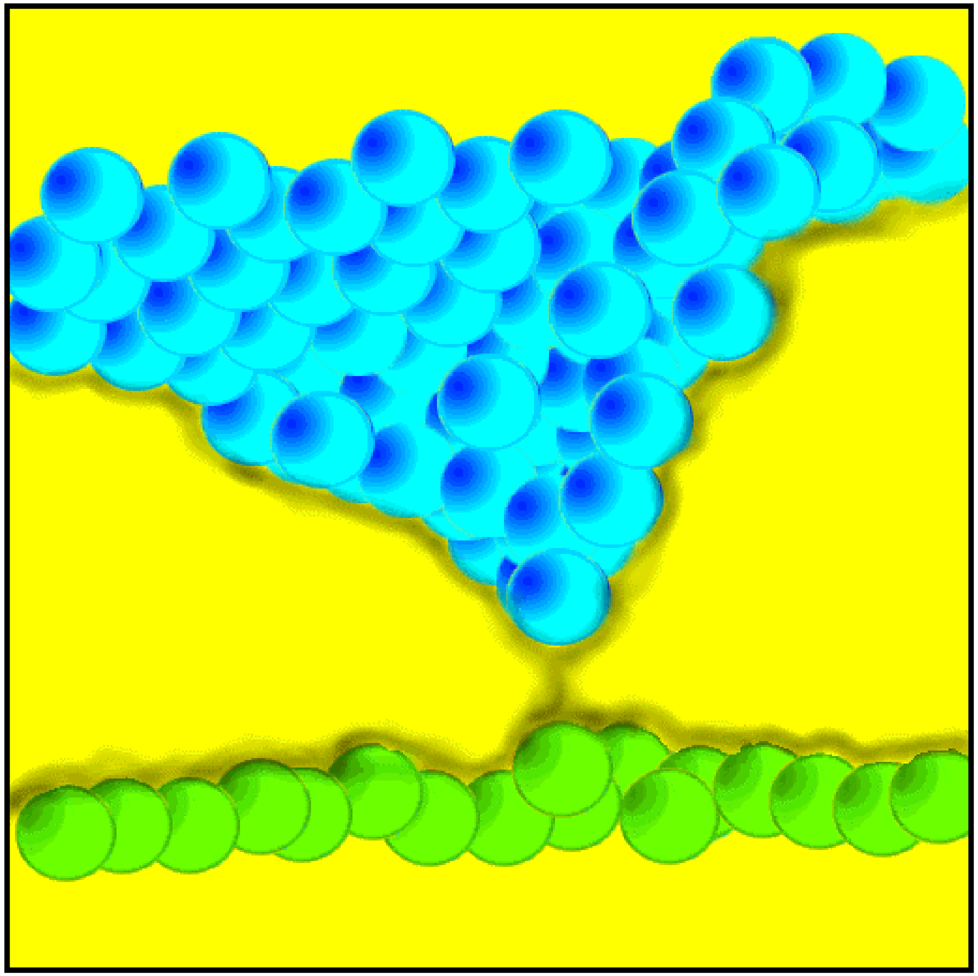




Electrical wiring at the nanometre scale



Point contacts in the scanning tunnelling microscope



- **Equations of heat transfer:**

$$\frac{\partial}{\partial t}(C_{el}T_{el}) = \nabla.(K_{el}\nabla T_{el}) - \beta(T_{el} - T) + Q$$

$$\frac{\partial}{\partial t}(CT) = \nabla.(K\nabla T) - \beta(T_{el} - T)$$

C is heat capacity, T is absolute temperature, K is thermal conductivity, Q is power input per unit volume, ß is a coefficient of heat transfer, "el" subscript refers to electrons.

- **At steady state,**

$$0 = \nabla.(K_{el}\nabla T_{el}) - \beta'(T_{el} - T) + IV / \text{volume}$$

(LARGE) **(SMALL)** **(LARGE)**

$$0 = \nabla.(K\nabla T) - \beta'(T_{el} - T)$$

(SMALL) **(SMALL)**

- **picture of heat transfer:**

electrons gain energy in contact; travel away from contact; then lose energy to lattice

• **Spontaneous photon emission should occur from high temperature electrons with a spectrum**

$$W(\nu) \sim \exp\left(\frac{-h\nu}{kT_{el}}\right)$$

Tomchuk and Fedorovich showed $\left(kT_{el}\right)^2 = (kT)^2 + \alpha IV$ **comparing energy losses from electrons to the lattice.**

(α is an empirical constant)

For $T_{el} >> T$ **, this reduces to** $kT_{el} = \sqrt{\alpha IV}$

so $$W(\nu) \sim \exp\left(\frac{-h\nu}{\sqrt{\alpha IV}}\right)$$

- **Either look at spectrum (variation of photon emission with wavelength, keeping power input constant) –> α –> electron temperature, T_{el}**

- **Or look at variation of photon emission with power input (=IV),keeping wavelength constant –i.e. look at narrow range of wavelengths**

$$\ln(W) = \frac{-h\nu}{\sqrt{\alpha IV}} + \text{constant}$$

- **keep $h\nu$ constant and vary IV. Slope of ln(W) vs. $1/\sqrt{IV}$ has a slope $\frac{h\nu}{\sqrt{\alpha}}$, so determine α.**

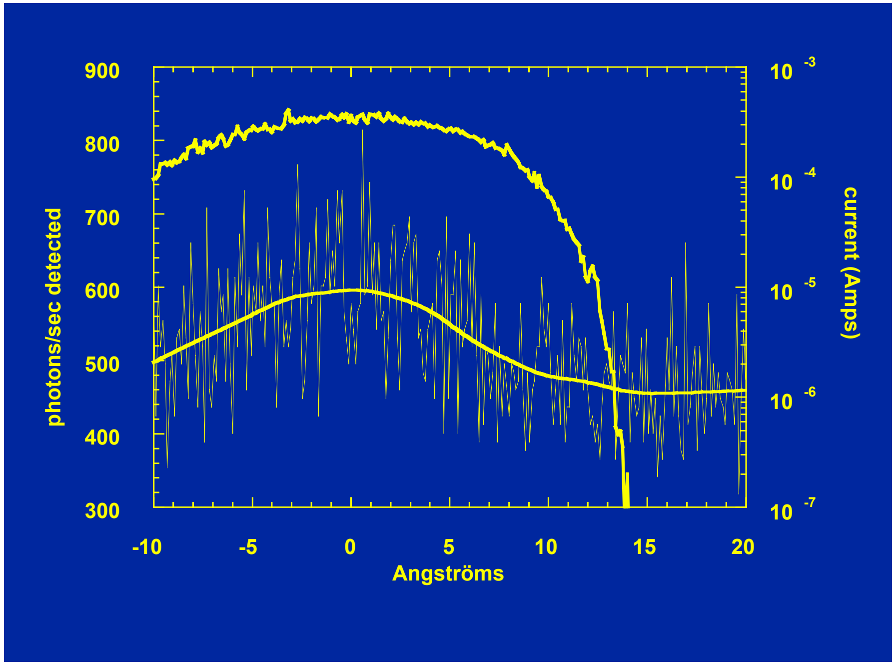
Then $kT_{el} = \sqrt{\alpha IV}$, so determine electron temperature

Experiments

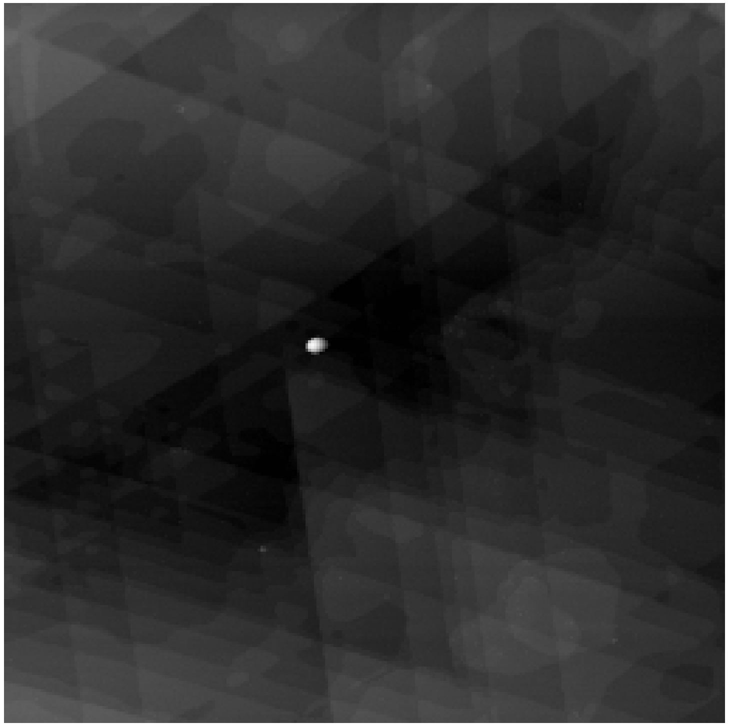
• UHV-STM operating at <10^{-10} mbar, with light collection a photomultiplier detection.
Combined detection efficiency 1.5%

• Apply 1.5V to contact – see light emission

1.5V bias, W tip, Au sample. Inserted 10Å from tunneling then retracted 30Å



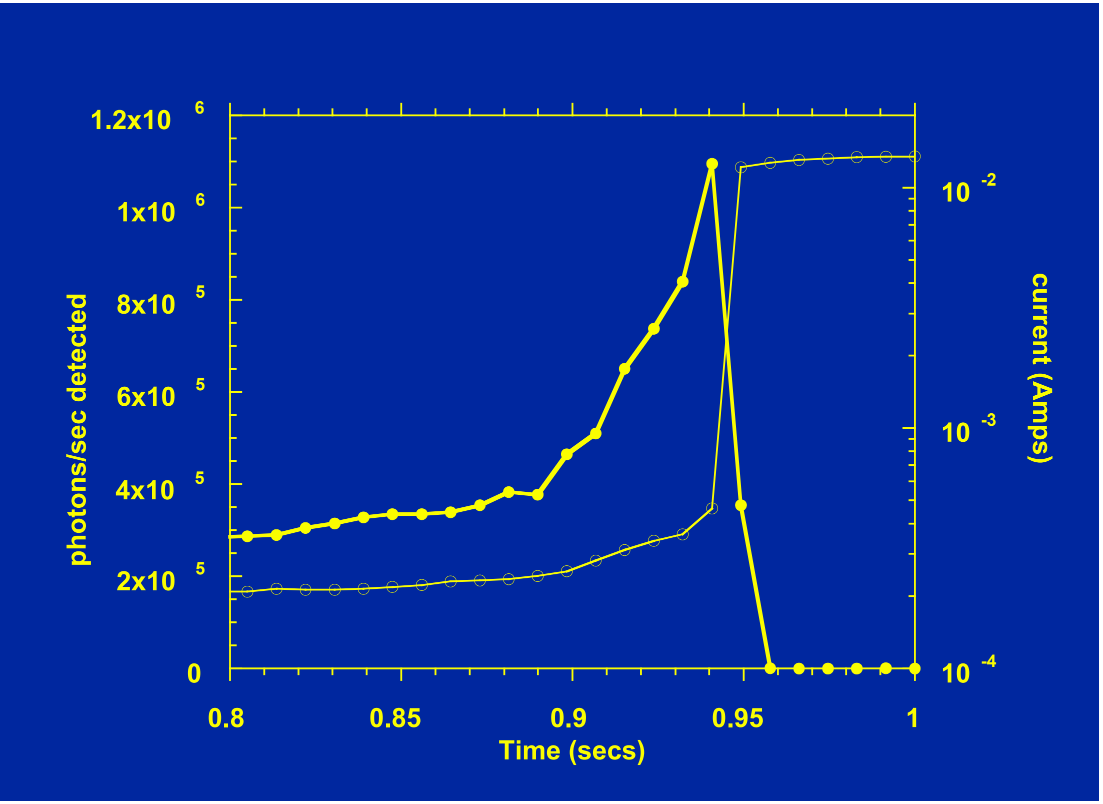
STM image after contact (5000Å x 110Å)



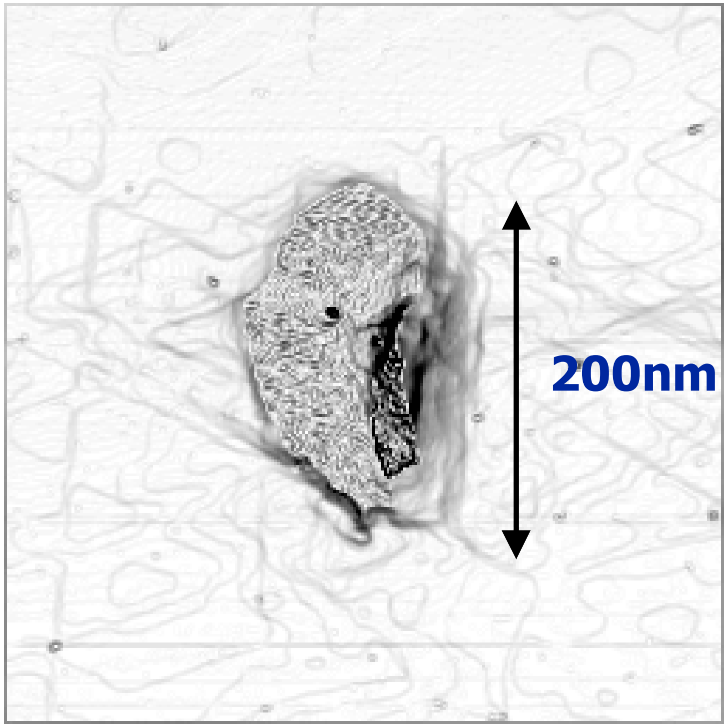
•Increase contact size:
more light emission and contact 'melts'

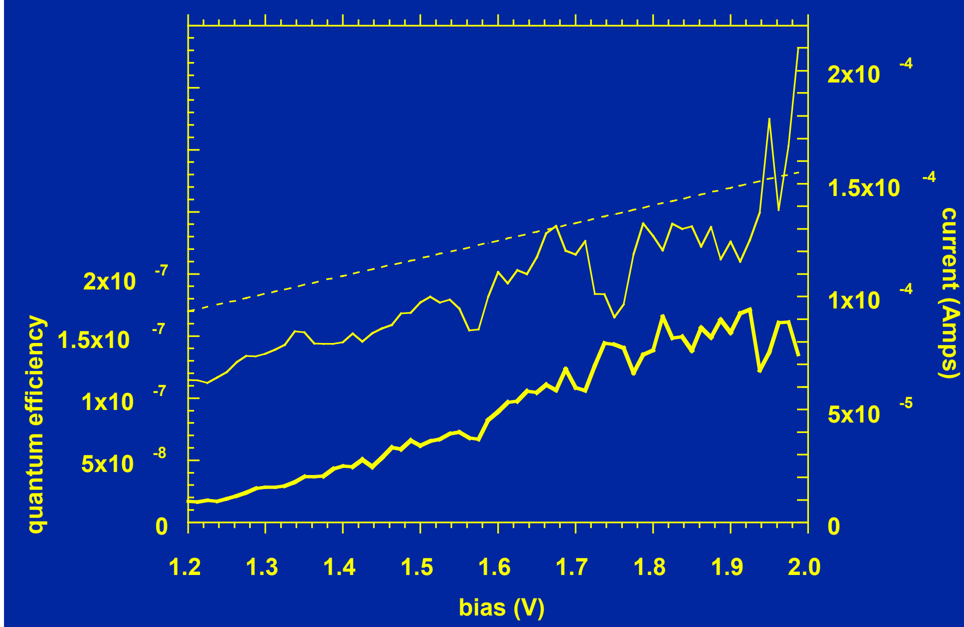
• As the contact size increases, photon emission first increases, then decreases in non-ballistic regime.

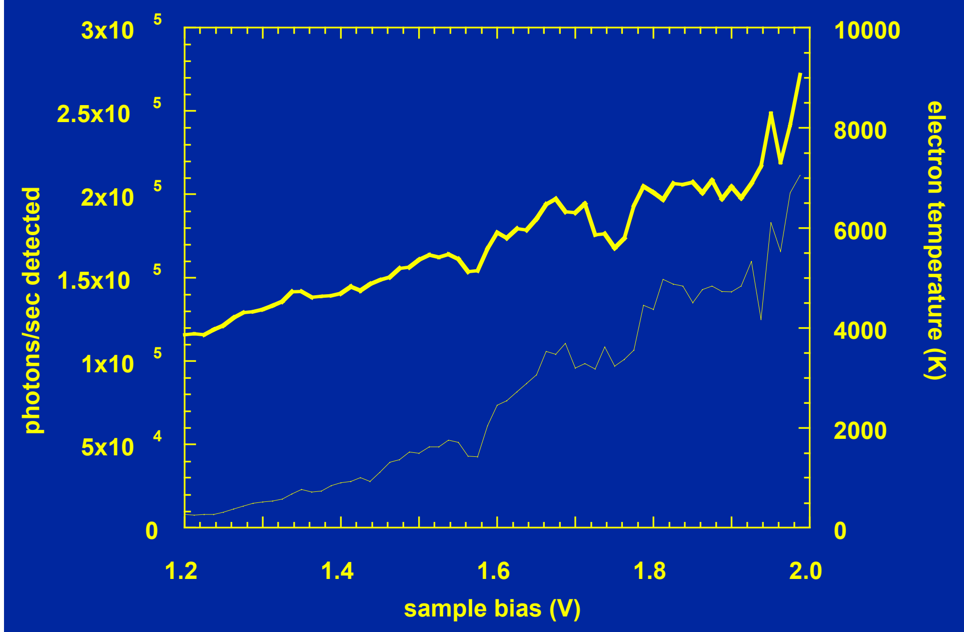
• Crater size matches critical L – bulk phonons



STM image of Au surface after contact was made





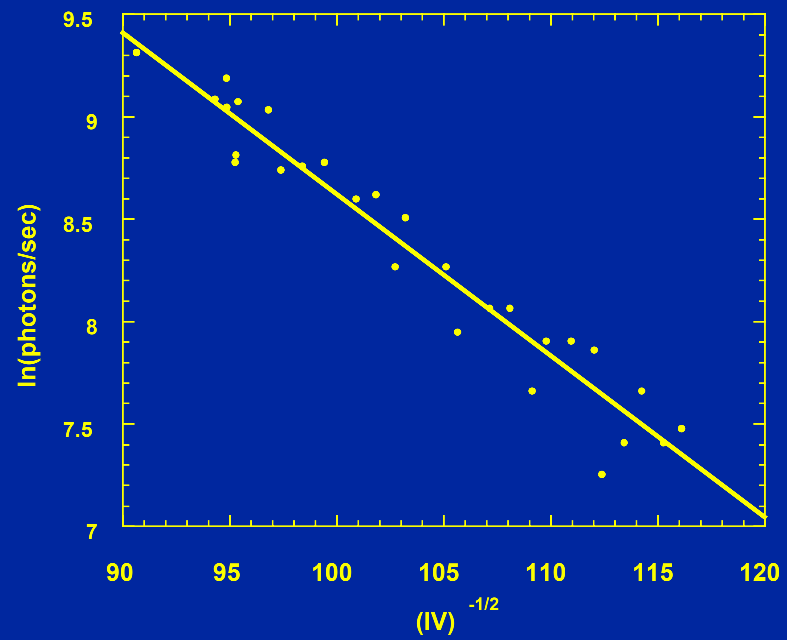


Photons counted over the range -1.7–2.5eV for a varying sample voltage with a single atom contact

Upper line: current
dashed line: current relating to one quantum
lower line: quantum efficiency

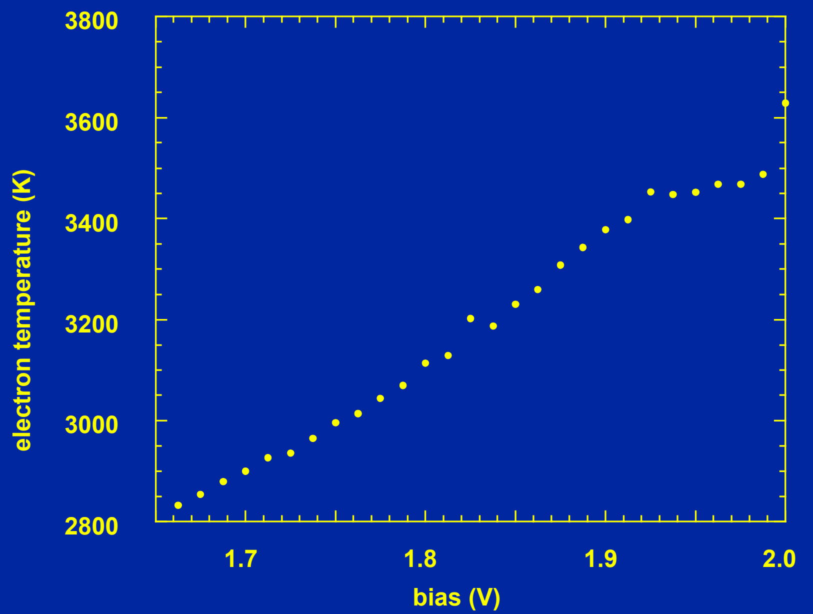
Thin line: photons per second detected

thick line: electron temperature for α=4.8 x 10^{-35} and hν-2.1eV.



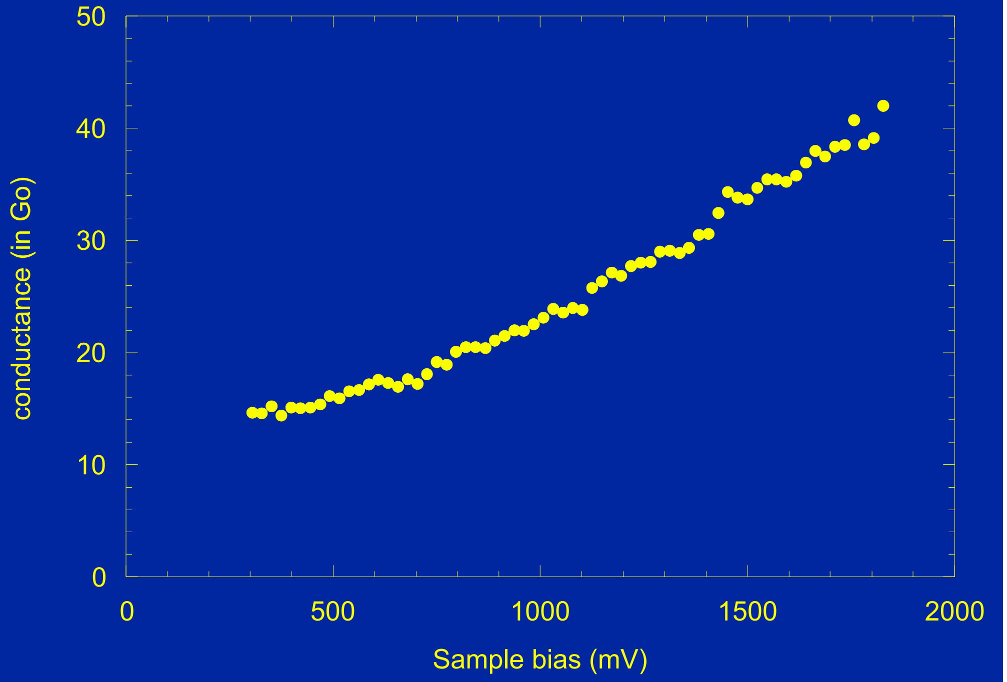
Now add a 2.4–2.6eV filter before PM tube.

Log plot of detected photons to determine the electron temperature. The range of counts per point is 12–94, and the slope is -0.079. Conductance of the contact ~0.4 quanta.



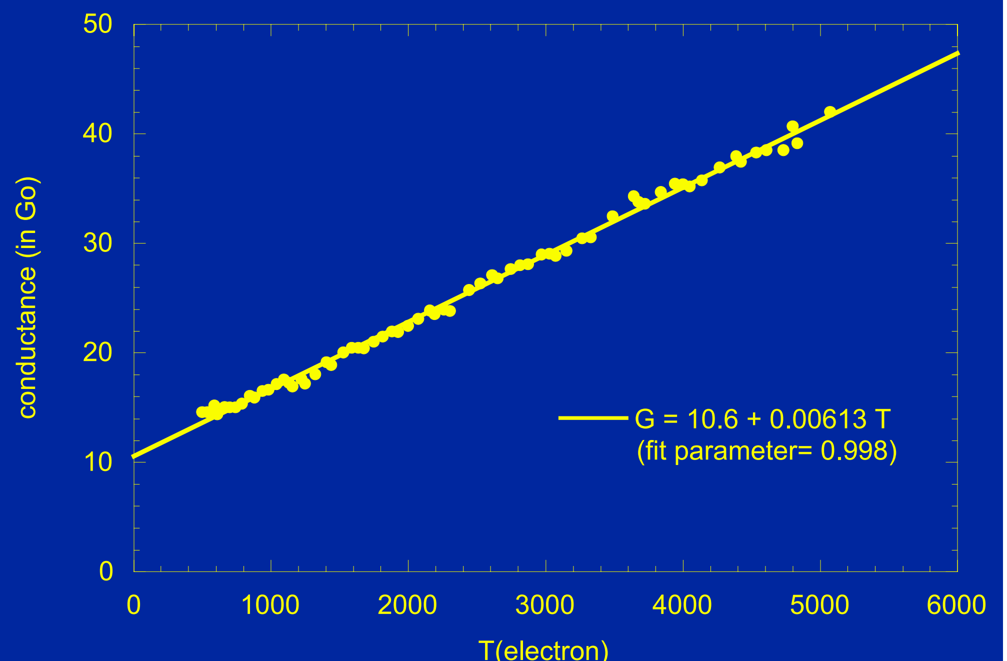
Electron temperature plotted as a function of bias, using the relation

$$kT_{el} = \sqrt{\alpha IV}$$



Non-linear conductance

For a contact of size ~10 atoms, conductance increases with bias.



Relation between conductance and electron temperature is very linear.

High current densities

Observe ~10^{15} Am^{-2} in stable contacts. c.f. ~ 10^{12} Am^{-2} necessary for macroscopic wires to fail. This higher stability is due to the lack of heat transfer between electrons and phonons in the contact.

This demonstrates that contacts below some critical size, L will have higher current-carrying capabilities

Other potential mechanisms to be ruled out:

- **ohmic heating –the electrons would be at a higher temperature than the melting temperature of the lattice.**

- **photon emission from the decay of some electron excitation –
can be discounted because of the form of the emission spectrum found here,**

$$W(\nu) \sim \exp\left(\frac{-h\nu}{kT_{el}}\right)$$

- **plasmon-mediated photon emission from the STM – requires the emitted photon energy to be no higher than the electron energy, but here 2.5eV photons were emitted for a bias of 600mV.**

Conclusions

- High current densities in nanowires
- Wires/contacts ~several nm in size stable at high current densities.
- For STM point contacts light emission consistent with high electron temperature.
- Divergence of electron and lattice temperature.

Acknowledgements

Andrew Downes
Colm Durkan
Andrew Hoole